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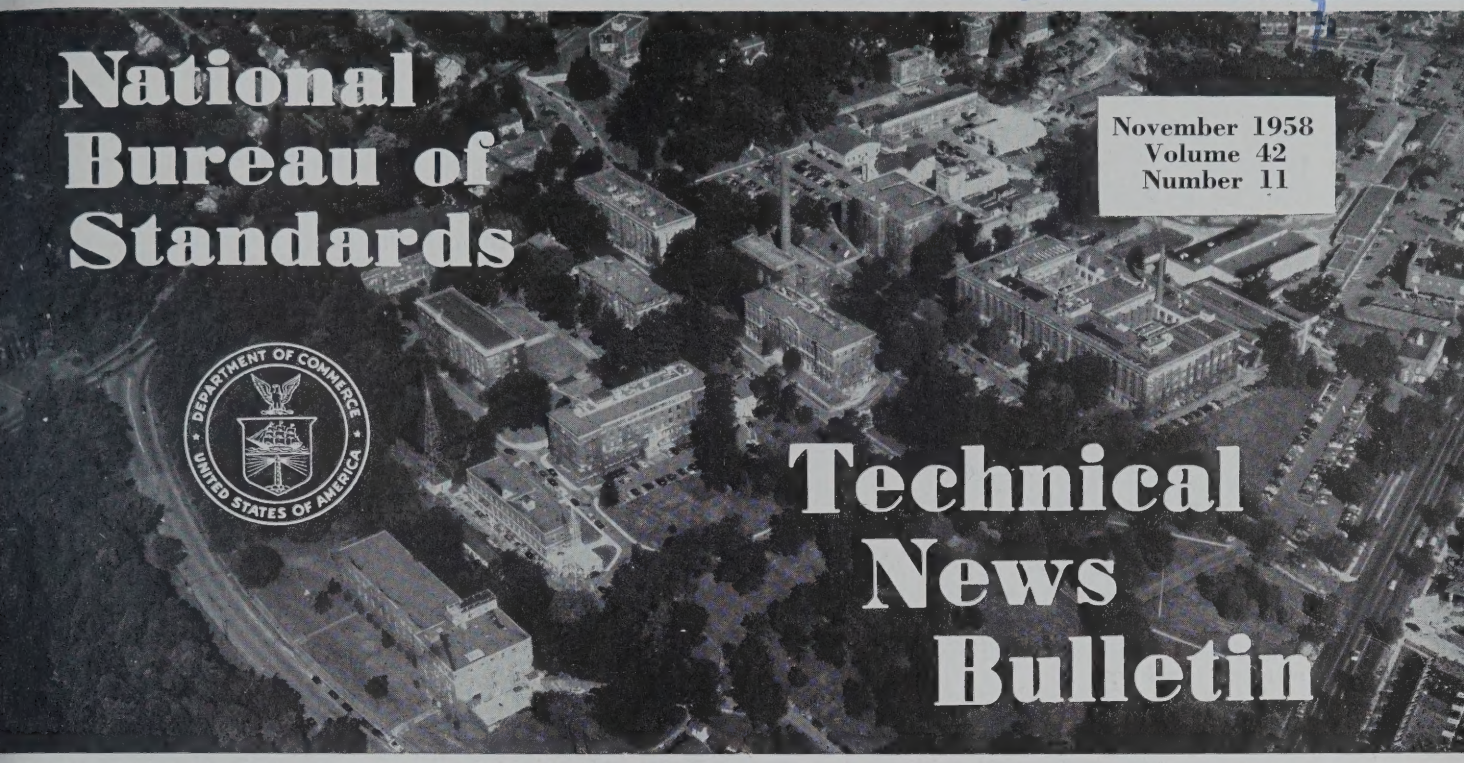


Technical News Bulletin

Conference on Electronic Standards and Measurements

OVER 870 scientists and engineers from industry, universities, and Government participated in a Conference on Electronic Standards and Measurements, held August 13–15 at the Bureau's Boulder (Colo.) Laboratories. Sponsored by the American Institute of Electrical Engineers, the Institute of Radio Engineers, and the Bureau, the three-day meeting provided an opportunity for exchange of information and ideas regarding the most recent developments in the field of electronic measurement. Thirty-six technical papers were presented, dealing with standards and measurement techniques for frequencies from direct current into the microwave region, the relations of the primary standards to physical constants, and the most effective methods of organizing and operating a standards laboratory.

Implicit in the program of the Conference was the recognition that accuracy in electronic measurements is more important today than ever before. Aircraft control, rocketry, and missile guidance all require highly specialized electronic equipment. In order for this equipment to work together as a unit, each of the separate components must be specified, constructed, and evaluated according to accurately calibrated reference standards. Very slight deviations from electronic specifications may result in complete failure of a missile or other device.

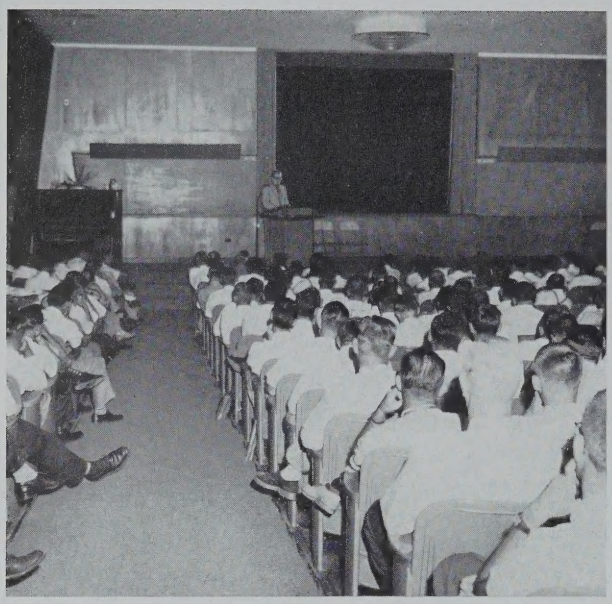
Yet the electronics industry has expanded so rapidly that it has been impossible for research in electronic standards to keep pace with this development. Individual laboratories have been forced to set up their own reference standards, which naturally differ from those of other laboratories. In the resulting uncertainty regarding component specifications, electronic units are being built and used without precise knowledge of how well they will operate or how long they will last.

The critical importance of this situation was brought

also in this issue . . .

Dedication of the NBS Electronic Calibration Center . . . page 220 . .

New Services and Facilities Announced . . . page 223 . . .



Final session: **Speaker is Lt. Francis L. Roach, Department of the Navy. The heavily attended Conference spilled over from the Boulder Laboratories' auditorium (shown here) to other lecture rooms.**

sharply to a focus in the technical sessions of the Conference, where the large attendance and the nature of the discussions made it evident that both industry and Government are aware of the urgent need for universally accepted, consistent standards in the electronic field.

The technical sessions of the Conference were preceded by formal dedication of the new NBS Electronic Calibration Center (p. 220). Following this ceremony, Dr. Allen V. Astin, Director of the Bureau, set the theme of the meeting in his opening address, "Standards and Measurements for Electronics". Dr. Astin was introduced by Conference Chairman Bernard M. Oliver (Hewlett-Packard Co.). The delegates also heard a talk by Robert C. Sprague, Chairman of the Board of the Sprague Electric Company, at a Conference luncheon on August 14. The technical program, arranged under the chairmanship of I. G. Easton (General Radio), consisted of six technical sessions on: (1) The Relationship of Standards to Physical Constants; (2) Frequency and Time Interval Standards; (3) Direct-Current and Low-Frequency Standards; (4) Radio Frequency Standards; (5) Microwave Standards; and (6) The Organization and Operation of Standards Laboratories.

Session 1. The Relationship of Standards to Physical Constants

The first session of the Conference, presided over by J. M. Richardson (NBS Boulder Laboratories), was an examination of the status of presently accepted standards, the information available on the universal physical constants, and the relationship between man's arbitrary magnitudes and nature's fixed values. Recent determinations of two physical constants, the proton gyromagnetic ratio and the acceleration due to gravity, were discussed, and new work on relating the standard of length to the wavelength of an atomic transition was presented.

R. D. Huntoon (NBS) pointed out that measurements may be made in terms of our national standards of mass, length, and time, with probable errors at present of about 3 parts in 10^9 for 1-kg mass, 3 parts in 10^8 for 1-m length, and 1 part in 10^8 for 1-sec time. As length and time can be expressed with even greater precision in terms of physical wavelengths and atomic transition frequencies, it is desirable to relate these standards to such physical constants. However, in spite of the precision of the fundamental standards, the precision of derived standards is considerably less. Here again an exact knowledge of physical constants is required to improve the standards. For example, if current and potential difference standards are to be improved, a more exact knowledge of g, the acceleration due to gravity, is needed, since this constant enters into the measurements through the force exerted by the current.

H. Preston-Thomas (National Research Council, Canada) reported on a new method of determining g, to an expected accuracy of about 2 ppm, by timing a body in free fall. This method offers great advantages over the usual physical pendulum method, which is limited by systematic errors related to the nature of the knife-edge, and flexure of the pendulum and its support while swinging.

P. L. Bender and R. L. Driscoll (NBS) reported their recent determination of the proton gyromagnetic ratio in a weak field by a free-precession technique (see p. 217). The earlier work of Thomas, Driscoll, and Hipple in 1950 had made the proton resonance a universally available standard for the calibration of any magnetic field to 22 ppm. The present work reduces the error of the earlier determination by a factor of four. The new value will serve to improve the accuracy of experiments for determining the universal physical constants, and may also be used to check the constancy of the ampere as maintained by the Bureau.

K. G. Kessler, R. L. Barger, and W. G. Schweitzer (NBS) discussed their work on an improved optical wavelength standard. The method increases accuracy and precision by increasing the sharpness of the wavelength line. This is accomplished by reducing the Doppler line width, the breadth due to the motion of atoms toward or away from the observer. The light emitted by a collimated beam of mercury atoms excited by electron bombardment is viewed at right angles to the motion of the atoms, which therefore appear to be standing still. The wavelength is thus defined at least 5 times more sharply than in other methods.

J. W. M. DuMond (California Institute of Technology) discussed his research on a special group of constants of fundamental significance in physical theory, often called the atomic constants or the universal physical constants. They include the velocity of light,

Excerpts—CONFERENCE KEYNOTE ADDRESS

Allen V. Astin, Director, NBS

The present conference, however, is a larger undertaking. It will give wide attention to the problem of basic standards as they relate to the whole spectrum of measurement in the electronics field rather than to the limited area of high frequency. . . . The theme of this conference is to integrate the structure of our complicated requirements for reliable electronic measurements involving all the manifold electrical, radio, and microwave quantities and the basis of these quantities in fundamental definitions and prototype standards. . . .

The most predominant characteristic of modern standards is their dynamic nature. First, accuracies are continually being increased, and second, the range of conditions for which standards are required is continually expanding. . . .

Another requirement for useful standards at any time—but particularly critical for modern standards—is that they be rigorously consistent within the whole chain of measurement, leading back to the international prototype standards representing the fundamental units of mass, length, and time. . . .

A third characteristic of modern standardization is that we are making effective steps to move away from arbitrary prototype standards as the basis of measurement to a reliance on natural constants. . . . The advantage of natural constants over arbitrary prototype standards is clear. If properly chosen, natural constants afford greater opportunities for increased accuracy and stability. These constants are also, so to speak, freely available to all scientists and to all laboratories. There will be less dependence on elaborate calibrations based on national prototype standards, and a central standardizing laboratory will be able to spend more of its time on measurement research and disseminating information on the techniques of measurement.

This country is now faced with the following problem. The electronics industry has expanded so rapidly in the past decade that its needs for standards and measurement techniques and for an orderly, interrelated system of measurement units have outstripped the development of standards and related services.

Today we know of problems resulting from inefficient data exchange and uneconomical interchange of materials and components. . . . We at the National Bureau of Standards are gravely concerned about the problem. The Department of Defense is also troubled by this situation. It was at the urging of the Department of Defense that the NBS Electronic Calibration Center was planned and today put formally into operation. In addition to this Calibration Center, there have been established in the past few years a number of standards centers within the Department of Defense and in industry to help meet this current problem. The Electronics Calibration Center of the Bureau will seek to provide focus and assistance to these other centers in order to establish a strong self-consistent measurement chain throughout the country. The means by which we go from the basic standards to the production line is worth special consideration, and I am pleased to note that the last session of this conference is devoted to this problem.

It is through standardizing laboratories which directly service industry that measurement has its greatest impact upon technology. The problem is to create a system by which the service provided by each of these standardizing laboratories is consistent with all the others. In this way it becomes possible to create a universal meaning in the interchange of information or materials or components throughout industry. The National Bureau of Standards serves this end.

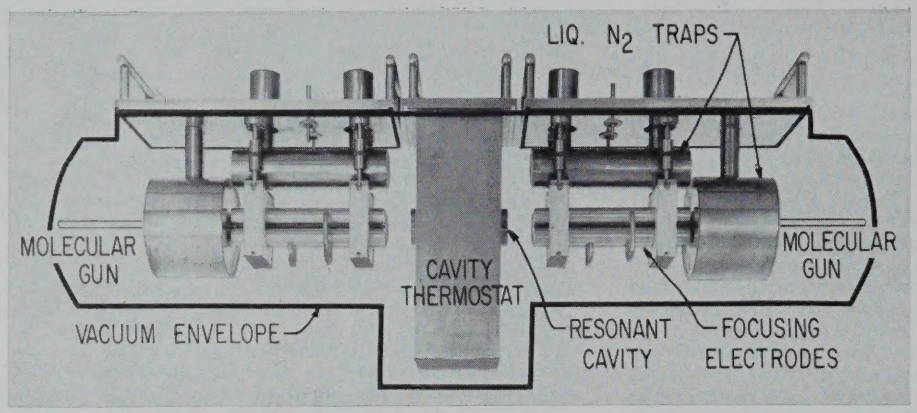
. . . In terms of sheer efficiency, a central standards laboratory reduces the number of intercomparisons sharply as the number of standards laboratories in industry and Government is increased . . . a central organization reduces the probability of error, assures a systematic progression from the basic standards, and provides for the effective network of all standards—for example, voltage, power, impedance, capacitance, inductance—tied to the standards of length, mass, and time. The importance of these interrelationships is often forgotten when we get to that end of the measurement spectrum we call production.

the electronic charge and mass, the fine structure constant, the faraday, the Rydberg constant, Avogadro's number, Planck's constant, and Boltzmann's constant. The close interrelationship of these constants was pointed out. In spite of the appeal in defining all units according to the values of three or four universal constants, such an attempt is premature. At present, lack of guidance for the choice of the best fundamental quantities and lack of exact knowledge of the values of these constants prevents such a changeover. From a practical standpoint it is better to rely on presently available natural embodiments of our units, such as the optical wavelength standard, determined to parts in 10^7 and precise to parts in 10^9, and the cesium frequency standard, recently determined to 2 parts in 10^9 and demonstrated to be precise to a few parts in 10^{10}.

Session 2. Frequency and Time Interval Standards

Under the chairmanship of W. A. Edson (General Electric), six related papers on the generation, transmission, and intercomparison of radiosignals, having great precision of frequency or timing, were presented.

The first report, by A. W. Warner (Bell Telephone Laboratories), explained the place of high-quality quartz-crystal oscillators in the over-all system of frequency standardization. Quartz crystals operating at frequencies of a few megacycles have Q values of several million at room temperature and about 50 million at the temperature of liquid helium. Frequency stabilities of a part in 10^{10} are readily achieved for



Double-beam ammonia maser (*Session 2, Frequency and Time Standards*). Under study at the Boulder Laboratories, the maser shows considerable promise as a frequency and time standard.

short periods, and may be maintained for periods of several weeks by extreme care in orientation, mounting, and temperature control of the plate.

A second paper presented by W. P. Mason (Bell Telephone Laboratories) described basic research in solid state physics, aimed at isolating and reducing the sources of internal friction in crystalline quartz. Outside the temperature range 35° to 150° K, the internal friction is nearly all connected with crystalline dislocations. It appears that significant improvements in the Q and aging rate of quartz resonators may be achieved by improving the preparation of synthetic quartz, once the basic mechanisms involved are understood.

S. N. Kalra, R. Bailey, and H. Daams (National Research Council, Canada) discussed a cesium beam frequency standard, which differs only slightly from the Atomichron. The cesium beam itself may be regarded as a precision frequency discriminator which is used to correct the frequency of an independent free-running oscillator. This oscillator should have the greatest possible stability on both long- and short-term bases. It is thus possible to maintain a time and frequency standard having great absolute precision, even though the cesium reference is used only occasionally and briefly. The construction and operation of the Canadian frequency standard was described in some detail, and its performance was stated to approach 1 part in 10^{10}.

The advantages of the ammonia maser as a primary frequency standard were described by R. C. Mockler, J. Barnes, R. Beehler, H. Salazar, and L. Fey (NBS). Existing masers have shown a short-term stability of 1 part in 10^{12} and a signal-to-noise ratio of 10^4. The principal remaining difficulty is to set and maintain the tuning of the maser cavity to coincide with the natural frequency of the molecular transition. Present units may be set and reset to a precision of a part in 10^9. However, work now in progress points to a significant improvement in this performance. At the present time the ammonia maser appears unexcelled where extreme values of phase and frequency stability are required for very short and moderate intervals of time.

A. O. McCoubrey (National Company) reported on an intercomparison of two Atomichron cesium beam standards. These two production-type Atomichron units were transported from Malden, Mass. to Teddington, England, where they were compared with the cesium beam standard of the National Physical Laboratory. The two Atomichrons differed from each other by only 1 part in 10^{10} and differed in frequency from the British standard by only 3.5 parts in 10^{10}. These results support the belief that it is now possible to establish a primary frequency standard having an absolute precision of about 1 part in 10^{10}, without reference to any other frequency standard.

The final paper, presented by J. A. Pierce (Harvard University), gave recent results achieved in the comparison of frequency standards over long distances. The frequency of radio station WWV at 5 Mc was measured by observing the phase drift of the demodulated seconds pulse. By restricting observations to the E-layer transmission obtained during the daylight hours, daily measurements were made with a standard deviation of about 4 parts in 10^{10}. A similar precision was achieved in frequency comparisons by observing carrier phase shift at 19.6 kc on signals transmitted across the Atlantic Ocean. Comparisons accurate to a few parts in 10^{11} were achieved by phase shift at a transmission frequency of 60 kc between Boulder, Colo. and Cambridge, Mass. In view of these results, it may be concluded that low-frequency transmission provides a method for making very precise frequency comparisons over great distances.

Session 3. Direct-Current and Low-Frequency Standards

Under the chairmanship of C. Peterson (NBS), the session on standards of direct current and low frequency opened with introductory remarks by F. B. Silsbee (NBS). The papers that followed covered diversified topics in the frequency range of interest, 0 to 30 kc.

G. H. Rayner (National Physical Laboratory) outlined the derivation of basic electrical units from a

computable standard of mutual inductance and a standard of time. This calculated standard provides the basis for the realization of the units of resistance and capacitance at NPL. The unit of resistance is determined by use of an a-c bridge network containing two mutual inductors and two resistances, and capacitance measurements are made with a bridge in terms of mutual inductance and resistance. Self-inductance can also be derived from mutual inductance by means of a bridge.

G. D. Vincent (Epply Laboratories) reported on the development, construction, and maintenance of standard cells. The characteristics of cadmium cells, in particular, were considered. Attention was also given to improvements, and needs for further improvements, in these "zero-frequency" standards of voltage.

The crossover from fundamental d-c standards to the measurement of alternating voltage and current was discussed by F. L. Hermach (NBS). Transfer instruments provide the vital link. Electrodynamic, electrostatic, and electrothermic transfer instruments are available and provide an accuracy of better than 0.1 percent at power and audiofrequencies. Future advances in design may well result from an amalgamation of classical instrument design with modern electronic techniques.

An illustration of such an amalgamation was given by R. F. Estoppey (Weston Instruments) who reported on an inductronic electrodynamometer. This instrument, which is capable of precise measurement of

Excerpts—CONFERENCE LUNCHEON ADDRESS

Robert C. Sprague, Chairman of the Board, Sprague Electric Co., and Director and Past President, Electronic Industries Association

With reference to the electrical industry, I look upon the Bureau's activities in two broad time scales. During the first 50 years of its existence (starting in 1901), the major portion of the standards effort was successfully devoted to the establishment of basic electrical standards—voltage, current, time, capacitance, inductance, and resistance. For the second half of the century, a large percentage of effort in this area will be concerned with electronics . . . .

Although progress in the field of fundamental capacitance, inductance, and resistance measurement has developed to a very high degree . . . we must continue serious work in these basic areas . . . .

Right now, secondary capacitance standards are available in values of 1 μf, as a maximum. Even so, there is a dearth of reference standards for small phase angles in the order of 1/10,000 of a radian. As of this date, the most precise calibration equipment available can give small phase-angle accuracies of but 5 percent to 200 percent (more accurately stated in terms of "conductance") for audiofrequencies applied to capacitors up to 1 μf. With the trend of electronic design creating the need for production-line components with near-theoretical characteristics, the development of these low-power factor standards must come, and must come soon . . . .

. . . The rapid advancement of the entire state of the electronic art, since World War II, has spotlighted an increasingly urgent need for more comprehensive and even more precise standards, terminology, and measuring methods . . . .

The program in standards for electronics is generally advancing on a broad technical front. In some specific areas, however, further attention is needed to support the mushrooming, highly technical electronic data-processing industry.

I have specific reference to the magnetic components used for memory elements, memory driving and switching transformers, and logical devices such as shift registers. Each of these critical elements employs an approximately square loop-type magnetic material, usually in the form of a toroid . . . the operation of these elements depends upon the application of a pulse of energy and the output is also a pulse of energy. This is in distinct contrast to the direct-current and 60-cycle energy previously applied to materials of this sort . . . the direct-current and low-frequency alternating-current characteristics of the basic magnetic material have no direct bearing on the behavior under pulse conditions, in which relatively steep wavefronts are present . . . . In the computers . . . many thousands of these individual elements are commonly used together . . . although the individual output of such a single device needs only to be what is called a "one" or a "zero", each of which may have a relatively broad tolerance, the effect of these tolerances is additive . . . a series-connected string of such cores may well develop a spurious "one" signal . . . it absolutely defeats the whole purpose of the computer and, in an extreme example, might direct a defense missile against the wrong target.

So I feel that pulse characteristics of magnetic materials represent an area in which standards are badly needed, both in measurement technique and in the standard element itself. At the same time, one must recognize that little progress can be made in a permanent way until standards of terminology are determined . . . .

While on the subject of pulse measurements, let me say this about the primary measuring device—the oscilloscope . . . utilized in lieu of more adequate standards . . . the oscilloscope of today falls far short of the requirements of the people who use it. These people need greater stability, higher frequency range, and greater trace definition.

I have tried to summarize for you two of the problem areas with which I am familiar. I am certain that they represent but a very small share of the total problems in the electrical area and, of course, but a minuscule part of the over-all national and international standardization of physical quantities.

The challenge facing us in the standardization field cannot be minimized . . . . We cannot go forward without a firm and comprehensive foundation. To give us that foundation is the mission of the National Bureau of Standards and the purpose of this conference.

The dry static calorimeter (*Session 4, Radio-Frequency Standards*) serves as a transfer standard between accurately known values of d-c power and r-f powers to be measured. It has a dynamic range extending from 20 mw to 12 w, and a frequency range from dc to 300 Mc.

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voltage, current, power, and energy, was originally developed as a product resolver. It was to be used for the multiplication of two electrical inputs to produce a d-c output accurately related to the product of the two input currents. The instrument consists of an electrodynamometer mechanism and a permanent-magnet moving-coil mechanism with a common staff. The two mechanisms are connected in such a way that the restoring torque for the dynamometer is supplied by the permanent magnet. Torque is automatically balanced by a sensing element and a feedback amplifier, which produces a current in the d-c element to balance the dynamometer torque exactly. In its extended form, the unit measures volts, amperes, and watts within 0.1 percent over a frequency span from 0 (dc) to 2,500 cps. Energy is measured by connecting the output of the inductronic wattmeter to a precision integrator.

The last two papers dealt with recent work on methods and apparatus for the precise measurement of small capacitance. The first of these papers by A. M. Thompson (National Standards Laboratory, Australia) was delivered by F. K. Harris (NBS). Although the basic ideas presented were not new, their application has been carried to limits previously unattained. A computable capacitance standard can now be used to calibrate working standards in a wide range of values. It is also possible to measure with certainty quantities as small as a few μpf (10^{-18} f).

The final paper by M. C. McGregor (National Standards Laboratory, Australia), J. F. Hersh (General Radio), R. D. Cutkosky (NBS), F. K. Harris (NBS), and F. R. Kotter (NBS), described new apparatus for absolute capacitance measurement, recently constructed at the Bureau. The techniques used were those developed by Thompson in Australia. A transformer bridge was assembled having a least count of 10^{-6} pf when operated at a 20-v level at 1 kc. This constitutes both a substantial improvement in precision and an extension of range at the Bureau. The assignment of capacitance values is limited in accuracy only by the determination of the length of an end-standard gage bar. (See p. 229.)

Session 4. Radio-Frequency Standards

The session on radio-frequency standards, presided over by D. C. Ports (Jansky and Bailey) demonstrated the increasing interest in continuous-wave unbalanced power, impedance, attenuation, and voltage, as well as field strength, noise, and interference in the 30 kc to 1,000 Mc spectrum.

The equipment that is available for the calibration of such rf quantities at the NBS Electronic Calibration Center was discussed by M. C. Selby (NBS Boulder). Calibration of power, voltage, attenuation, and field strength at 30 kc to 300 Mc and higher frequencies is routinely possible. Novel features of the equipment that permit operation in this range were reported.

The Bureau's standards of impedance in the 30 kc to 300 Mc range were given special attention in a paper by R. C. Powell, R. M. Jickling, and A. E. Hess (NBS Boulder). In addition to a discussion of the primary standard and how it is obtained, comparison methods used in calibrating the working standards and instruments were reported. The paper included a survey of the equipment used in the new Electronic Calibration Center to make impedance measurements for other laboratories. Particular emphasis was placed on ranges and accuracies of such measurements. Terminals, the most critical elements of an impedance, were carefully analyzed, and standard terminals adopted by the Bureau were described in detail.

G. U. Sorger, B. O. Weinschel, A. L. Hedrick, and S. R. Raff (Weinschel Engineering) described the calibration of signal generator output voltages in the range of 100 to 1,000 Mc. The advantages and disadvantages of various calibration methods as applied to high frequencies were considered. This discussion included methods involving the direct and indirect measurement of output voltage. A system employing an intermediate frequency substitution method was

described in detail. In this system, a linear mixer converts the unknown signal to an intermediate frequency, which is then compared to a known signal, set by a piston attenuator.

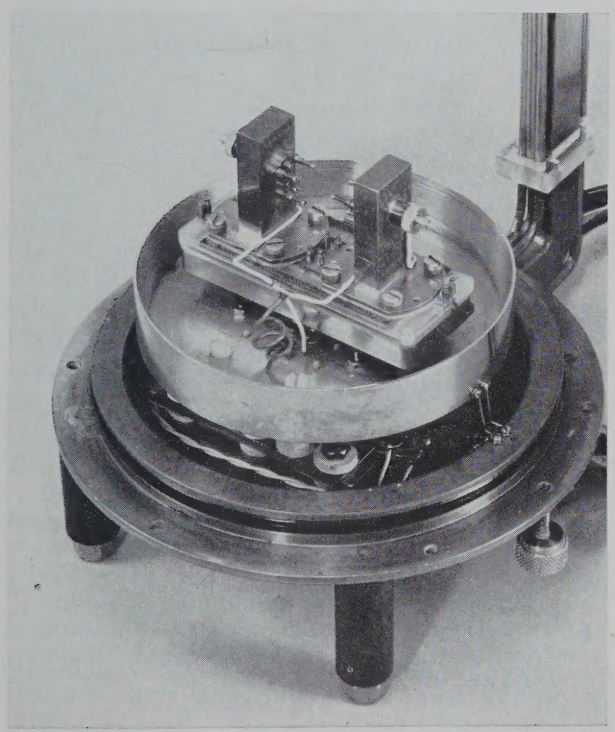
A paper on the design and development of a standard white noise generator was presented by H. Zucker, Y. Baskin, and S. I. Cohn (Armour Research Foundation); and I. Lerner and A. Rosenblum (U. S. Army Signal Corps Engineering Laboratories). The generator operates in the frequency range 0 to 1,000 Mc. Its principle of operation is Nyquist's law relating the noise output of a resistor to temperature. The generator consists of a low-reflection termination heated in a coaxial furnace to 1,400° C.

P. A. Hudson and C. M. Allred (NBS Boulder) reported on a dry, static, calorimetric rf wattmeter developed for the Electronic Calibration Center. This wattmeter serves as a transfer standard between accurately known values of d-c power and the rf power to be measured. The dynamic range of the instrument extends from 20 mw to 12 w, overlapping the range of another standard, a 0- to 100-mw thermistor bridge. The frequency range is 0 to 300 Mc. Analysis of errors indicates a maximum uncertainty of 0.5 percent in the wattmeter measurement of rf power. Results obtained with this instrument were found also to agree within 0.5 percent with the results given by other methods. This accuracy represents a significant improvement over the best presently available commercial instruments in the power and frequency range under consideration.

A survey of the problem of radio-interference measurement was presented by R. M. Showers (University of Pennsylvania) and W. E. Pakala (Westinghouse Electric). Although extensive radio-interference measurements have been made during the last 25 years, the complexity of the measurements and the varying accuracy requirements have made standardization difficult. In recent years, however, agreements on measurement techniques for most devices and systems have become common, and instrumentation standards, although complex, appear to meet present needs. In the field of instrumentation for interference measurements, in addition to requirements for antenna and gain standardization in common with field-measuring equipment, requirements are also placed upon various integrating types of detectors, band-width characteristics, response to both impulse- and random-type signals, and overload characteristics. However, much work remains to be done before optimum measurements leading to significant data on interference effects are possible. Measurements are presently made over the frequency range 14 kc to 10,000 Mc and beyond.

Session 5. Microwave Standards

Refined X-band microwave microcalorimeter (*Session 5, Microwave Standards*), featuring greatly improved ambient temperature control. This instrument permits the determination of the effective efficiency of a bolometer mount to an accuracy of better than 0.5 percent.

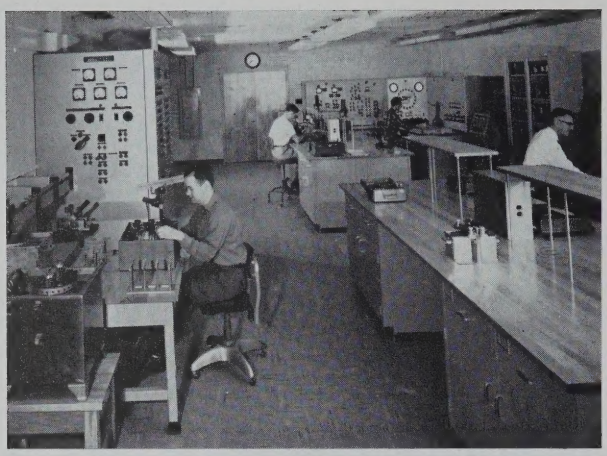


Methods of improving measurements at microwave frequencies received primary emphasis in the session on microwave standards, under the chairmanship of D. D. King (Electronic Communications, Inc.).

G. F. Engen (NBS Boulder) reported on recent advances at the Bureau in the field of microwave power measurements. One such development is an improved microwave microcalorimeter for evaluating bolometer mounts in the WR–90 (X-band) rectangular waveguide. This instrument, which features improved stability, resolution, and flexibility, is accurate to within 0.2 percent. Another development is a technique, based upon Kerns' impedance method, which yields measurements of bolometer mount efficiency agreeing within 0.5 percent with values provided by the microcalorimeter. A method for the accurate intercomparison of bolometer mounts was also described.

The operation of bolometers at liquid helium temperature was described by D. L. Birx and N. Fuschillo (Franklin Institute Laboratories). The sensitivity of bolometer power measurement is ultimately limited by noise so that at room temperature accurate measurements cannot be made of rf powers below one μw. However, operation of bolometers at liquid helium temperatures was found to lower the noise level, reduce specific heat, and permit the utilization of extremely high temperature coefficients of resistance. This allows measurements to be extended to much lower limits, 10^{-16} w.

The use of gas discharge noise sources as possible microwave noise standards was reported by K. W. Olson (Bendix Aviation). A standard microwave noise



Typical calibration services room (*Session 6, The Organization and Operation of Standards Laboratories*). A part of the new Electronic Calibration Center is shown.

source is needed above 290° K at levels of 10 to 20 db. Such a source can be readily developed from a gas discharge. A specific electron temperature exists in the positive column of a given gas discharge and over a particular band this results in a well-defined noise output. As discharge tubes with high stability and good reproducibility for use at S-band frequencies are commercially available they may be considered for use as microwave noise standards.

R. W. Beatty and D. M. Kerns (NBS Boulder) reported on recent developments by the Bureau's Boulder Laboratories in the field of microwave impedance. New impedance standards and measurement methods of increased accuracy were discussed. The standards are half-round inductive obstacles in rectangular waveguides. Measurements of the VSWR (voltage-standing-wave ratio) of these standards by an advanced technique agree with calculated values to within 0.05 percent. A number of new measuring techniques were also described. Among them were magnified and squared VSWR response systems and a modified reflectometer technique.

M. Magid (Hughes) spoke on precision microwave phase-shift measurements in a microwave bridge circuit. The phase shift from the test instrument is compared with that from a standard phase shifter consisting of a short circuit and a tuned directional coupler, by means of a special two-channel nulling arrangement. The system, which is self-checking, has been experimentally used to calibrate precision phase shifters, and results were compared with those from other short-circuit phase-standardization techniques. With WR–90 (X-band) waveguide, the new method was found capable of high accuracy.

A precision calibrator for microwave demodulators was described by J. Gindsberg (Raytheon). The calibrator is a portable precision generator of modulated signals. Fed from an external continuous-wave source, a ferrite modulator generates odd- and even-order signal components which are compared in a power bridge. In this way, the modulation level is calibrated by means of a precision variable attenuator and a directional coupler. Several successful models in WR–90 (X-band) waveguides have been built. They have no measurable calibration disparities and yield linear phase modulation up to 0.6 radian with excellent AM suppression.

Session 6. Organization and Operation of Standards Laboratories

The dedication of the new Electronic Calibration Center provided an appropriate occasion for a session describing the organization and operation of standards laboratories. Under the chairmanship of J. N. Whitaker (Hughes), five papers were presented on this general subject, and a sixth paper was given on uniform nomenclature of standards. C. E. White (AVCO R.A.D.), J. N. Whitaker (Hughes), and L. B. Wilson (Sperry Gyroscope) each spoke on the roles which their companies—representative of the industries engaged in the design and production of military equipment—are playing in the application and formulation of electrical and electronic standards. F. L. Roach and M. L. Scroggs (Navy) discussed the calibration program within the Department of the Navy, which is essential for the success of shipborne and airborne equipment as well as modern weapons systems. The standardization program for the AEC Atomic Weapons System was described by H. C. Biggs (Sandia Corp.)

All speakers emphasized that electronic standards laboratories have come into existence in recent years to meet new situations in the production and operational use of weapons and other complex devices of the space age. The Navy reported that measurements on complex weapon systems now require accuracies of 0.1 percent compared to 5 and 10 percent a few years ago.

To meet present needs, it was indicated that a standards laboratory must be equipped to cover the frequency range from direct current through at least 40,000 Mc. The usual practice is to have three operating units, one for dc and low frequency, another

All papers presented at the Conference will be published in a special issue of the Transactions of the IRE Professional Group on Instrumentation. Copies will go to all members of this group automatically. Additional copies will be available for sale to PGI members at $1.00, to IRE members at $1.50, and to nonmembers at $3.00. Orders should be mailed to the Institute of Radio Engineers, Inc., 1 East 79th Street, New York 21, N. Y.

for high frequency (rf), and a third for microwaves. Some laboratories also have "physical" standards units for calibrating mechanical and dimensional standards.

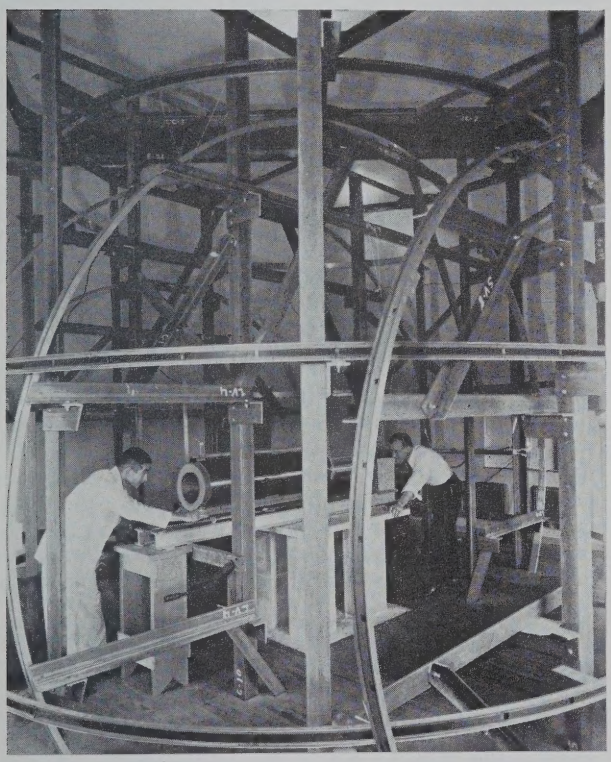
The feeling was expressed that standards laboratories must be under the control of a responsible group that is relatively independent of other operations. Only then can they reach their full potential in maintaining an echelon of high-accuracy standards that will inspire confidence on the part of those who use them.

The older laboratories have developed well systemized records for case histories of their standards, including detailed calibration data, copies of certificates, repair information, and evaluation data. In time, such records can provide useful statistical information.

All laboratories reported the use of environmental control, at least for the more critical areas. Temperature and humidity control can be obtained within narrow limits without too great an expense or difficulty. Air cleansed of dust is a desirable feature.

Although management may question the expense of a standards and calibration laboratory within their organization, once in operation there is no question of its justification. Today it becomes almost mandatory for the manufacturer of highly complex equipment to inaugurate his own standards program to remain in business.

The final paper, presented by A. G. McNish (NBS), pointed out the present inconsistency in nomenclature for standards and offered some corrective suggestions. The same set of standards is often called "primary" for one purpose, and "secondary" for another purpose. Therefore, it is desirable to classify standards in categories according to their nature. Study of standards shows that all of the various types in use may be classified into the same general categories. The first of these is the prototype category, which includes the standards from which all others are derived. Within each category can be established hierarchies indicative of the rank of the various standards and their relative accuracies. These hierarchies are designated by such terms as reference standards or working standards.



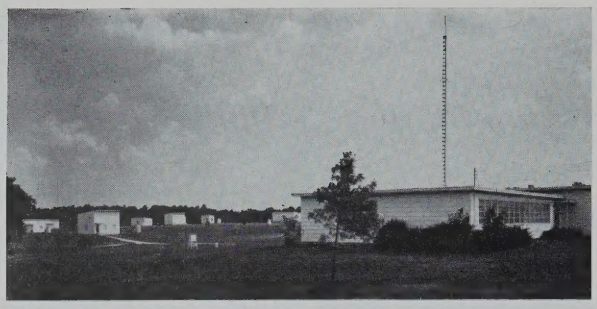
Apparatus used to redetermine the gyromagnetic ratio of the proton, or hydrogen nucleus. The solenoid (center), whose magnetic field can be precisely calculated from its known dimensions, causes the protons in a water sample to precess with an accurately measurable frequency. The proton gyromagnetic ratio is then calculated from the precession frequency and the precisely known field strength. The large coils which surround the apparatus counterbalance the earth's magnetic field.

Gyromagnetic Ratio of Proton Redetermined

THE GYROMAGNETIC RATIO of the proton—a measure of its interaction with magnetic fields—has been redetermined by the Bureau with significant increase in accuracy. This result not only provides a better standard for magnetic fields but also makes possible more accurate values for many of the fundamental constants of physics whose values depend upon magnetic field measurements. Examples are the electron charge-to-mass ratio e/m, the magnetic moment of the proton, and Planck's constant h.

The redetermination was made by R. L. Driscoll and P. L. Bender using facilities provided by the Fredericksburg Magnetic Observatory of the U. S. Coast and Geodetic Survey.

The new value for the proton's gyromagnetic ratio will be especially useful in the design and development of scientific and industrial apparatus in which it is important to know accurately the spatial distribution of a magnetic field or to regulate it closely. Here the proton can be used as a very sensitive probe to determine magnetic intensity in terms of the precisely known gyromagnetic ratio. Problems of this sort arise widely in the use of scientific apparatus—cyclo-



View of the Fredericksburg Magnetic Observatory showing buildings used by the Bureau in its redetermination of the proton's gyromagnetic ratio. At right is the control building containing electrical measuring equipment. The second building from the left is the nonmagnetic building in which the experiment took place (closeup, right).

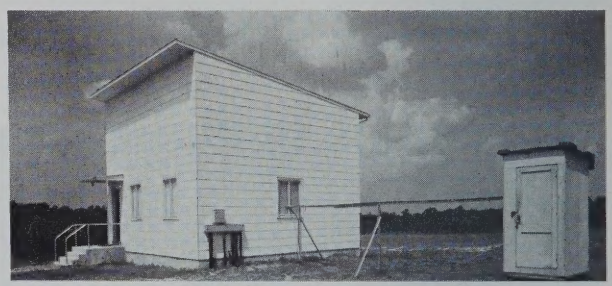
trons, mass spectrographs, and beta-ray spectrometers—and in industrial equipment such as servomechanisms and electromagnets.

The present work was carried out as part of a broader program which seeks to obtain more accurate values for important constants, such as the velocity of light, the acceleration of gravity, and the various atomic constants. These constants of nature, when determined to extremely high accuracy, provide invariant bases for the reproduction of many physical quantities such as length, time, and electric current. They thus serve to lock present standards and units of physical measurement into the phenomena of science. Because the proton's gyromagnetic ratio is basic to the determination of many of these constants, it provides a connecting link between them and the accepted standards of measurement.

Glass sphere containing distilled water used as a proton sample in redetermining the gyromagnetic ratio of the proton.

Like other atomic nuclei, the proton, or hydrogen nucleus, behaves as a small magnet. When placed in a magnetic field, it tends to orient its axis along the direction of the field. However, the proton is also spinning rapidly about its axis, and the resulting angular momentum causes it to act like a gyroscope. Thus, instead of lining up with the field, the proton actually precesses about the field direction. The ratio of the angular precession frequency to the magnetic field strength gives the gyromagnetic ratio.

In 1949 H. A. Thomas, R. L. Driscoll, and J. A. Hipple made the first precise measurement [1] of the proton gyromagnetic ratio, using as protons the hydrogen nuclei contained in a small water sample. Their result was combined with other data to give a more precise absolute value for the proton magnetic moment than had previously been possible. More accurate values were also obtained for a number of the fundamental constants of physics, such as the electron charge-to-mass ratio and Planck's constant.



Exterior of nonmagnetic building (left) used to redetermine the gyromagnetic ratio of the proton. At right is the small building in which the proton sample is first strongly magnetized. It is then shot through the connecting pneumatic tube into an accurately measured solenoid within the nonmagnetic building.

In the 1949 measurement, the gyromagnetic ratio was determined by measuring the magnetic field and radio frequency required for magnetic resonance absorption in the proton sample. A strong magnetic field of about 5,000 gausses was used and its value was determined by finding the force exerted by the magnetic field on a wire carrying a known current. This magnetic field measurement was difficult and was the principal limitation on the accuracy of the result obtained.

The present method reduces the error of the earlier one by a factor of four by using simpler techniques that have been developed since 1949. In this method, the hydrogen protons in a water sample are caused to precess in a magnetic field, and the precession rate is obtained from the frequency of the voltage induced in a pickup coil surrounding the sample. The gyromagnetic ratio is then obtained as the ratio of the angular precession frequency to the field strength.

Increased accuracy is obtained by using a magnetic field that can be calculated to very high precision. This field is produced by an accurately measured current flowing through a solenoid whose important dimensions are known to 1 part in a million. However, as the field

Control room at the Fredericksburg Magnetic Observatory showing equipment used to measure the precession frequency of the protons in the water sample.

strength obtained in this way is only 12 gausses, spurious magnetic fields from other apparatus, electrical currents, or vehicles must be carefully avoided. For this reason, the measurements have been carried out at the Fredericksburg Magnetic Observatory of the U. S. Coast and Geodetic Survey. The Observatory is about 10 miles south of Fredericksburg, Va., on a site chosen to be as free as possible from magnetic field disturbances. A separate nonmagnetic building, with large coils for compensating the earth's magnetic field, was made available for the experiment. At this location man-made magnetic field fluctuations are negligible and corrections for variations in the earth's field can be obtained from the Observatory magnetograms.

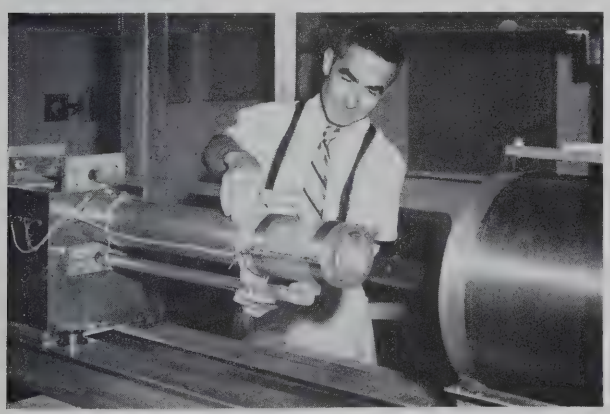
The proton sample consists of distilled water contained in a glass sphere about 2 cm in diameter. The sample is placed in a strong magnetic field in order to build up a large magnetization of the protons along the direction of the magnetic field. It is then shot about 15 m through a pneumatic tube into the center of the solenoid, within the nonmagnetic buildings. With the sample in the solenoid, a short pulse of radio-frequency magnetic field near the precession frequency is applied to tip the magnetic moments of the protons so that they are left nearly perpendicular to the magnetic field direction. They then precess about the magnetic field direction at a frequency corresponding to the strength of the field. The flux through a pick-up coil surrounding the sample changes at the same frequency at which the magnetization of the sample is precessing. The frequency of the induced voltage across the pick-up coil is measured accurately against standard frequency broadcasts by the Bureau's radio station, WWV, and the resulting value is combined with the magnetic field strength to give the proton gyromagnetic ratio.

A preliminary value of $(2.67515 \pm 0.00001) \times 10^4$ radians/(sec gauss), uncorrected for diamagnetism of the water sample, was obtained for the proton gyromagnetic ratio in terms of the ampere as now maintained at the Bureau. The value obtained in 1949 was given as $(2.67523 \pm 0.00006) \times 10^4$ radians/(sec gauss). If the present result is combined with a recent determination [2] by Driscoll and Cutkosky of the ampere as maintained at the Bureau in absolute units, the value becomes $(2.67513 \pm 0.0002) \times 10^4$ radians/(sec gauss).

[1] Measurement of the proton moment in absolute units, *by H. A. Thomas, R. L. Driscoll, and J. A. Hipple, J. Research NBS* **44,** *569 (1950) RP2104; see also* Magnetic moment of the proton, *NBS Tech. News Bul.* **33,** *57 (May 1949).*

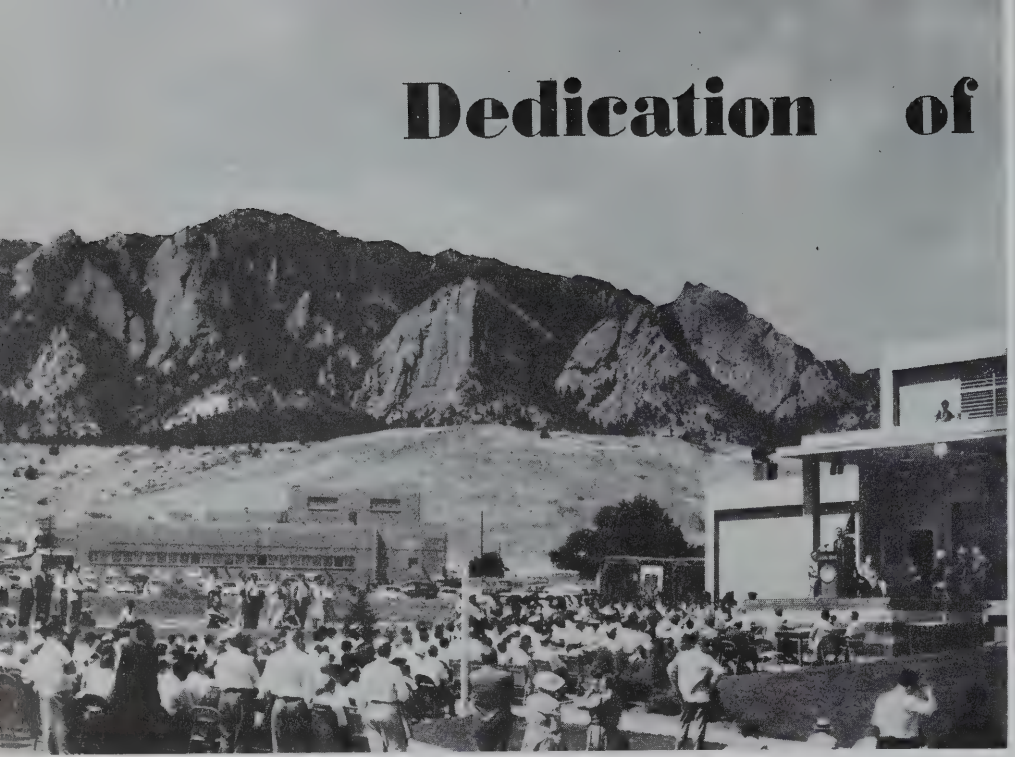
[2] Measurement of current with the NBS current balance, *by R. L. Driscoll and R. D. Cutkosky, J. Research NBS* **60,** *4 (1958) RP2846;* Measurement of current with a Pellat type electrodynamometer, *by R. L. Driscoll, J. Research NBS* **60,** *4 (1958) RP2845;* Redetermination of the standard ampere, *NBS Tech. News Bul.* **42,** *21 (February 1958).*

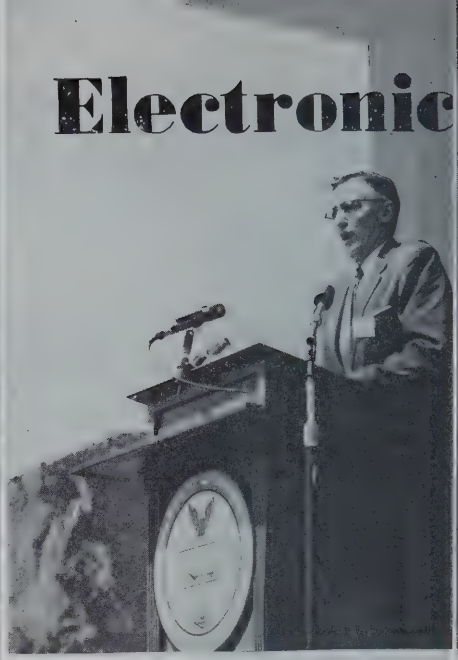
Compensating coils for making the magnetic field about the proton sample more homogeneous. The solenoid (right) has been moved aside. Above the compensating coils is the pneumatic tube used to carry the sample into the solenoid.



Large solenoid used to provide a precisely known magnetic field about the proton sample. The field produced by the solenoid can be calculated to high accuracy from its dimensions, which are known to 1 part in a million. Within the solenoid may be seen coils which surround the sample and are used to measure the precession frequency.

Dedication of Electronic





Left: A large audience of scient
to right): Dr. Allen V. Astin, Di
ment of the Army; Walter Willi

THE ELECTRONIC CALIBRATION CENTER of the National Bureau of Standards was formally dedicated at the Bureau's Boulder (Colorado) Laboratories on August 13, 1958. Housed in a new wing of the Radio Standards Laboratory, the Center provides Government, industry, and the military services with access to the nation's primary electronic standards. Here are calibrated the many reference standards of Government and industry which in turn are used to calibrate the instruments on production lines and in research laboratories—activities vital to the progress of future electronics programs in communications, automation, and space technology. This modern calibration facility will help the Bureau meet the ever-increasing need for still greater accuracy of measurement and for more precise electronic standards and instruments.

The dedication ceremony immediately preceded a three-day conference on electronic standards and measurements (see page 209). Dr. Allen V. Astin, Director of the National Bureau of Standards, welcomed the nearly 1,000 scientists attending from all over the country, and introduced the honored guests. After an invocation by the Reverend Robert L. Carlson representing the Ministerial Alliance of Boulder, Dr. Astin touched briefly on the origin of the Calibration Center and its establishment to fulfill the urgent need by Government, industry, and the military services for electrical and electronic standards.

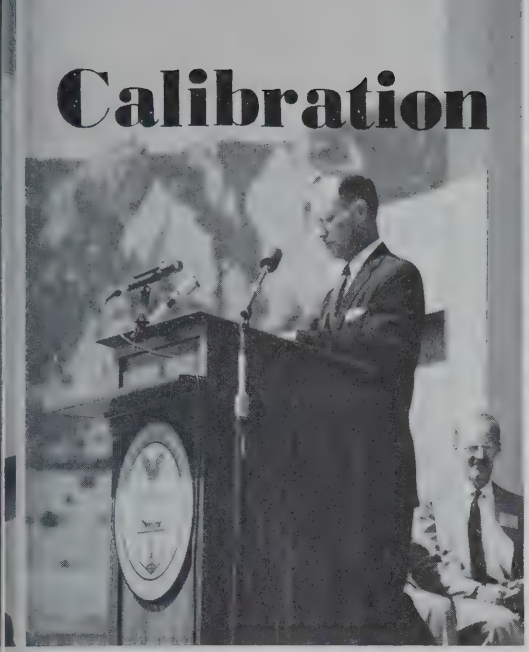
Under Secretary of Commerce Walter Williams, delivered the dedicatory address. Mr. Williams stressed the importance of the work to be done in the new $2.5-million Center. "This laboratory," he said, "will make possible the development and perfection of the standards needed for equipment in the age of interplanetary travel." He went on to discuss the important part the Center will play in achieving American aspirations and ideals.

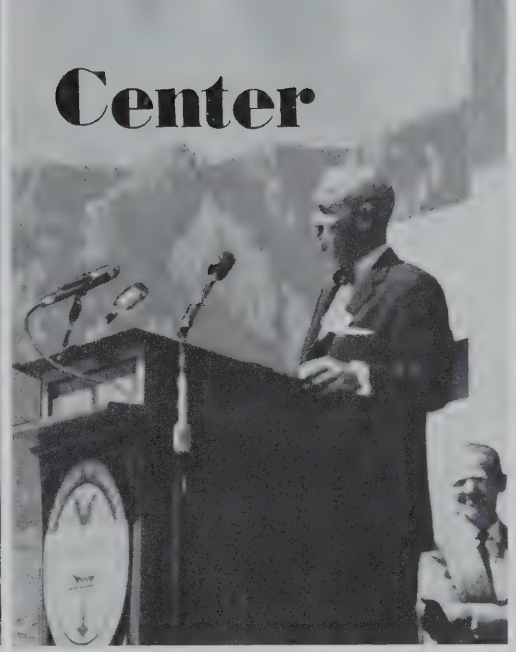
Speaking next on the program, for the Department of Defense, was Dr. Edward G. Witting, Deputy Director of Research and Development for the Department of the Army. He pointed out that the new Center will provide the military services with a sorely needed facility for assuring that their electronic equipment, now used in almost every conceivable application by the fighting forces and their supporting organizations, is maintained at the peak of accuracy. Dr. Witting noted that the facilities provided by the Calibration Center have been needed for a long time, both by military agencies and by equipment developers and manufacturers.

He told how the Air Force first approached the National Bureau of Standards about seven years ago with a comprehensive program for periodic calibration of electronic standards used in test and repair facilities of the Air Force depot system. "This program was so large in scope," Dr. Witting said, "that it was necessary to begin plans which resulted in the Calibration Center. As the program progressed, Army and Navy requirements for calibration services were developed and made known. As of now, the volume of work expected to be placed here by defense agencies totals almost 3,000 pieces of equipment to be calibrated a year at a cost of almost $1 million a year."

Dr. Witting concluded by voicing his expectation "that these requirements will increase substantially in the next few years, keeping pace with the growing dependence of the military on electronic devices in the execution of their missions."

Calibration Center





nd other invited guests gathered for the formal dedication ceremonies. *Above:* Speakers at the ceremony (from left r of the National Bureau of Standards; Dr. Edward G. Witting, Deputy Chief for Research and Development, Depart- Undersecretary of Commerce; and Robert C. Sprague, Chairman of the Board, Sprague Electric Company.

Speaking for the electronics industry, Robert C. Sprague, Chairman of the Board of the Sprague Electric Company, sketched the development of the industry from the first radios to the present. He emphasized the dependence of the electronics industry on accurate measurement and standardization techniques during the current missile and space exploration phases of the industry's development.

Mr. Sprague, who is also a member of one of the NBS advisory committees, said that the Bureau's program on standards for electronics "is generally advancing on a broad technical front" but that further attention is needed to "support the mushrooming, highly technical" electronics industry.

"The challenge facing us in the standardization field cannot be minimized," he said. "We have advanced the art beyond the wildest dreams" of the early workers in the electrical field. "Now our continued progress in the research and development fields depends primarily upon standardized terminology, adequate basic standards, and standardized precision measuring devices. We cannot go forward without a firm and comprehensive foundation. To give us that foundation is the mission of the National Bureau of Standards."

Commenting on the importance of the Calibration Center, Mr. Sprague said: "Today's long-range radar and missile guidance equipment could not possibly achieve the high degree of accuracy required of them by our military services if we did not have such reliable measurement services as are now available in the new Center here and the Washington laboratories of the Bureau."

In closing the dedication program, Boulder Mayor Leo C. Reithmayer, a professor of political science at the University of Colorado, hailed the dedication as a milestone, not only for the National Bureau of Standards and electronics, but for the City of Boulder. He predicted that the new Center would have a significant impact on future development of the city.

Pausing before a VHF bridge in the high-frequency impedance section, Dr. Astin, Dr. Witting, Mr. Williams, and Mr. Sprague (left to right), inspect the facilities and equipment of the new Center during the "open house" which followed the dedication ceremonies.

Construction Features

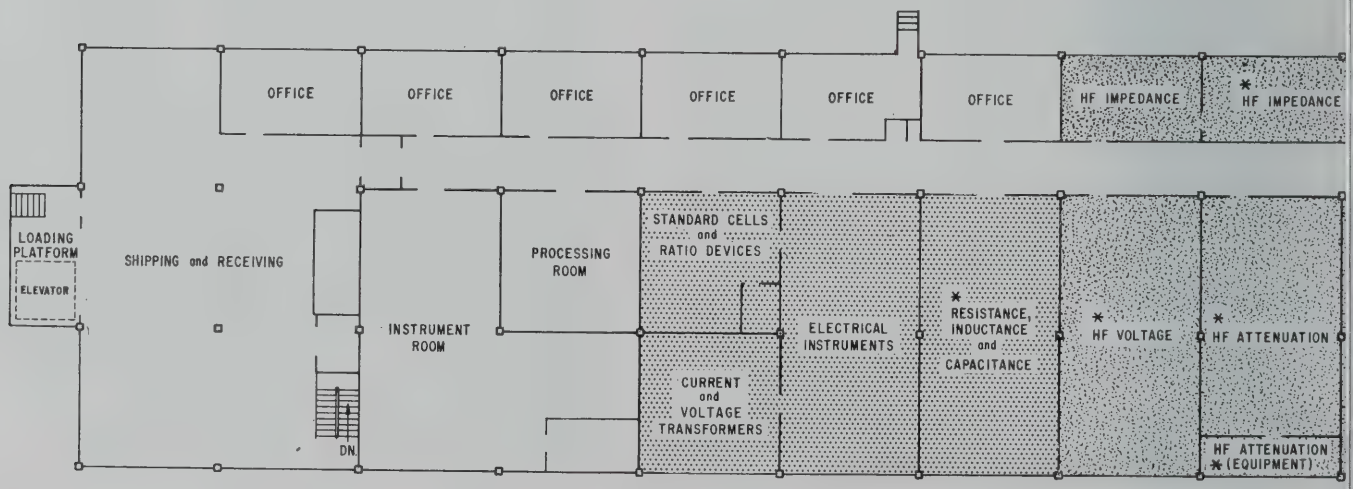
NBS Electronic Calibration Center

THE IMPORTANCE of proper enviroment for precision measurement operations is widely recognized. A well-lighted area that is free of mechanical vibration and shielded against radio and other electrical interference, that has regulated and well-filtered power lines, and dust-free air of controlled temperature and humidity, is essential to calibration work where the primary standards are concerned. All of these features have been incorporated into the new Center. In addition, nearly all of the electrical equipment has been installed in consoles, for the convenience of the operating personnel and for the protection of the sensitive equipment. Incorporating all the latest technological advances, this laboratory could well serve as a model for standardizing laboratories throughout the world.

The new wing, which houses the Center, is approximately 400 feet long by 72 feet wide, and contains 27 rooms. (See floor plan below.) Most of the wing is single-story, made of concrete supported by caissons on the bedrock to provide a vibration-free structure. In addition, blocks of concrete set in beds of sand beneath the building provide steady foundations for mounting sensitive instruments.

Eleven of the rooms are completely shielded with copper foil; special attention has been given to doors, dust openings, and ceiling light fixtures. Electrical power lines brought into the rooms are filtered and regulated, and carried in metallic conduits.

High-capacity air-conditioning equipment filters the dust from the air, and holds the temperature and humidity within close limits.



Services and Facilities of the

Electronic Calibration Center

THE PRIMARY MISSION of the Bureau's new Electronic Calibration Center is to calibrate interlaboratory standards for such quantities as voltage, power, and impedance in terms of the national standards maintained by NBS. These interlaboratory standards, in turn, are used to assure the accuracy of reference and working standards in laboratories, on the production line, and in overhaul stations throughout the nation.

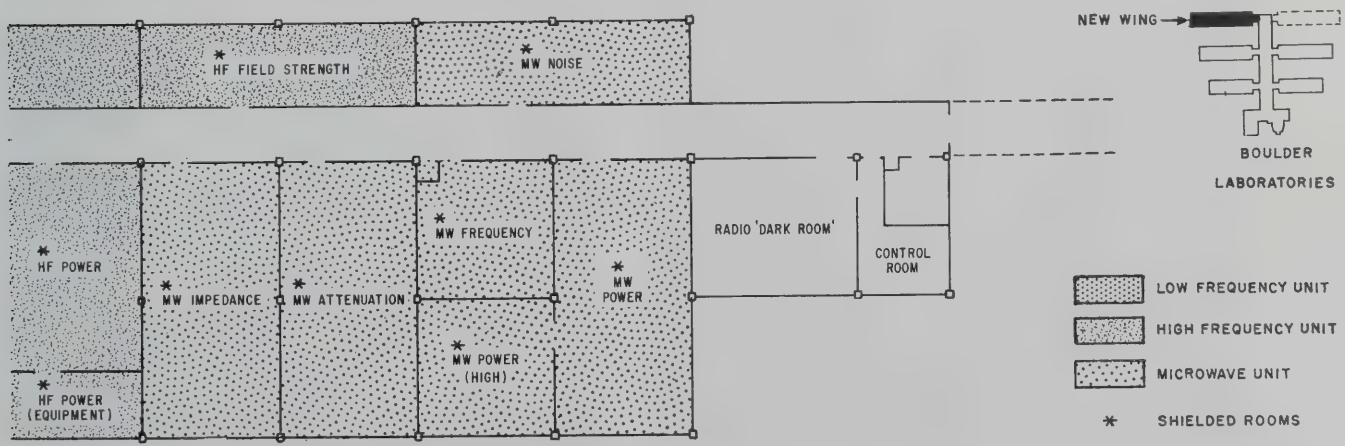
The quantity of electronic calibrations required today in the design, manufacture, and adjustment of extremely complex electronic weapons, communications equipment, and industrial electronic apparatus is so great that branching chains of measurement are necessary to extend the national standards to the shop or field instruments used for this work. The large number of links in each chain, through which the units of measurement must be transferred, requires the highest practicable accuracy at each step in order to assure adequate accuracy of the shop and field instruments. The Electronic Calibration Center is being equipped to meet these accuracy requirements while handling the increasing calibration workload.

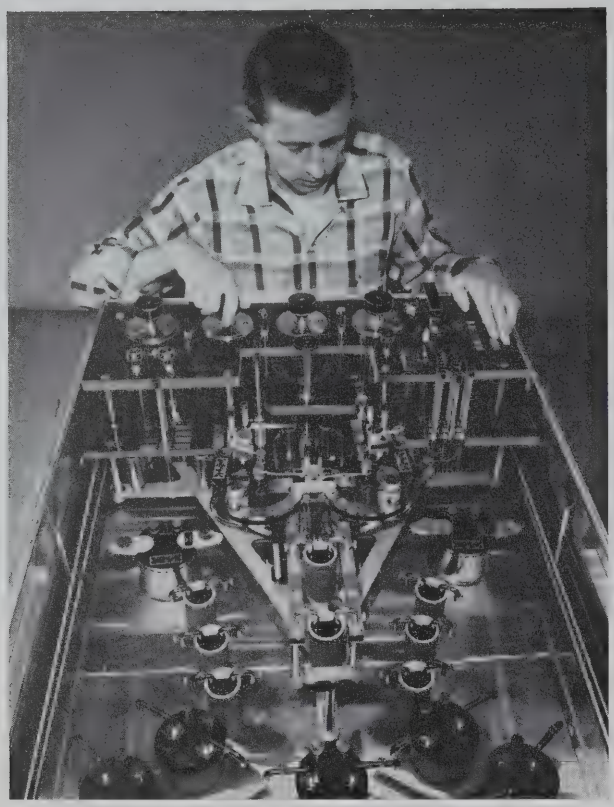
The fundamental system of electrical measurement now employed in the United States uses absolute units, that is, units derived from the fundamental units of length, mass, and time—the meter, kilogram, and second. Basic to the absolute system of electrical units are the absolute ohm and the absolute ampere. The absolute ohm is derived from the absolute henry, based on an inductor of accurately known dimensions. The absolute ampere is established in terms of the magnetic force on an accurately dimensioned current-carrying coil, measured with a current balance. These basic standards are maintained in the Bureau's laboratories in Washington, D. C.

Other units, such as the watt and the kilowatt hour, are obtained by combining these units and by extending the scale of measurement. The units then are transferred to higher frequencies by appropriate techniques.

Services offered by the Calibration Center cover three broad frequency ranges: (1) Low frequency (zero frequency through about 30 kc); (2) high frequency (30 kc through about 300 Mc); and (3) microwave (above 300 Mc).

Somewhat more than half of the initial instrumentation program has been completed, and the Center now is able to provide the most urgently needed services. Additional standards and instrumentation, beyond the present program, will be required in the future to replace those made obsolete by technological advances and to extend the capabilities of the Center as new calibration requirements arise. The eventual goal is to measure and standardize in the Center all electronic quantities for which there is a substantial calibration need. Calibrations required only infrequently may often be obtained elsewhere in the Bureau.





A group of extremely accurate, sealed double-wall 1-ohm standard resistors form the basis for resistance measurements made in the Electronic Calibration Center. The Wenner bridge shown here is used to calibrate these resistors.

Low-Frequency Region

In the low-frequency region (0 to 30 kc), the Electronic Calibration Center provides calibrations for such electrical standards as resistors, bridges, potentiometers, inductors, capacitors, standard cells, electrical instruments, ratio devices, and instrument transformers. These calibration services previously have been available only through the NBS Electricity and Electronics Division in Washington. They will continue to be available there as well as in Boulder and in some cases, over considerably wider ranges. In either location, calibrations will be made in terms of the national primary standards. In general, identical calibration accuracies will be achieved, and hence the decision to send a standard to Washington or to Boulder will usually be made on the basis of convenience.

Resistance Standards. The Bureau maintains the unit of resistance at its Washington laboratories by means of a group of ten extremely accurate, sealed double-wall 1-ohm standard resistors. Resistors of this type, compared frequently with the primary reference group, also form the basis of measurements made in the Electronic Calibration Center. It is expected that some of these resistors will become a part of the primary group. The resistance calibration services provided by the Center are limited to high or moderately high-precision apparatus.

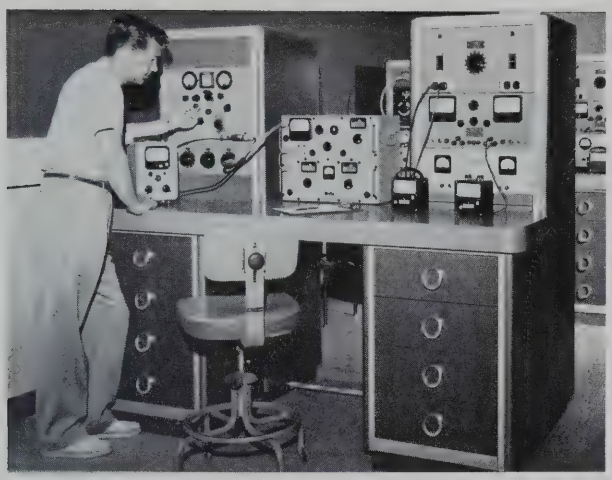
A Wenner bridge is used for calibrating standard resistors. This bridge incorporates a thermostatically regulated oil bath for maintaining the bridge and the resistors under test at a constant known temperature. It employs a direct-reading ratio set to compare resistors with known standards by either a Kelvin double bridge or a Wheatstone bridge. Resistance comparisons, using the Wenner bridge, can be made to 1 part in 10 million under optimum conditions.

The components of bridges and resistance boxes are calibrated with known standard resistors by use of a direct-reading ratio set. Potentiometers are calibrated with a Universal ratio set. With this device, the ratio of the potentiometer emf-dial resistance to the standard cell-dial resistance is determined for all settings of the emf and standard-cell dials.

Inductance Standards. Stable standards of self-inductance are used as components of a-c bridges and other circuits employed in impedance measurements. Such inductors ordinarily are used at fixed frequencies, usually 100, 400, or 1,000 cps. Because inductance standards are employed in bridge circuits where the current in the inductor is not accurately known, it is of greatest importance that the current coefficient of inductance be practically zero. This probably precludes the use of inductors having metal or metal powder cores as standards.

An "equal substitution" method using a Maxwell-Wien bridge is now employed in the Center. Three groups of calibrated inductors serve as standards.

An Anthony-pattern Wheatstone bridge, from the Army's Rocket and Guided Missile Agency at Redstone Arsenal, is calibrated at the new Calibration Center.



New consoles in the Electronic Calibration Center for use in measuring the characteristics of radio-frequency field-strength meters.

They can be intercompared frequently to detect relative drifts or changes. One group is calibrated periodically against the national standards of capacitance and resistance. It is anticipated that a precision Maxwell-Wien bridge will be constructed at the Center to measure a wider range of inductances and to double-check the stability of the standards.

Capacitance Standards. Fixed capacitors, with air dielectric for low values of capacitance and mica dielectric for higher values, are used as components of a-c bridges, as standards for the external calibration of bridges, and for the calibration of other standards by substitution techniques. Three-terminal capacitors are useful in certain types of bridges and in other measurement circuits where the direct capacitance is of importance. More often, three-terminal capacitors are used simply as two-terminal capacitors, with the case connected to one of the capacitance terminals. The Center is equipped to calibrate either type and can occasionally provide approximate conductance values where needed.

Equipment employed in the Center for calibrating capacitors consists of a capacitance bridge having internal capacitance standards which are, in turn, calibrated by step-up procedures using standard capacitors. Three groups of standard capacitors are available for intercomparison to detect relative drifts or changes. One group is calibrated periodically in terms of the national standard of capacitance.

Standard Cells. Weston-type cadmium standard cells are of two general classes: (1) Saturated cells, used principally for reference standards of electromotive force; and (2) unsaturated cells, used chiefly as working standards of electromotive force.

The Center is prepared to calibrate both types. With a microvolt potentiometer, they are compared directly to the saturated standard cells. These cells are compared periodically with the group of saturated cells which the Bureau uses to maintain the unit of electromotive force.

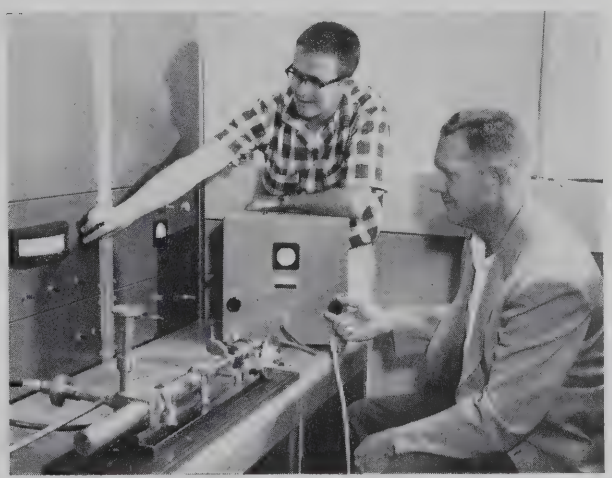
Because saturated cells have a temperature coefficient of about 50 μv/°C, the temperature at which they are calibrated must be very closely regulated. At present, facilities in the Center include temperature-controlled air baths which are constant within a few hundredths of a deg C. Consequently, the emf of standard cells can be measured with a precision of about 2 μv and can be certified to an accuracy of 0.001 percent. After installation of a temperature-controlled oil bath, even greater accuracy will be obtained. This installation should be completed by the end of 1958.

Unsaturated standard cells have rather low-temperature coefficients of approximately 5 μv/°C. Consequently, temperature control is not nearly as important as for saturated cells. Results of calibration of unsaturated cells normally are given to 10 μv, and the cells are certified to 0.01 percent.

Electrical Instruments. Indicating instruments are essential to the measurement of electrical quantities. Sometimes they are employed as reference instruments exclusively for calibrating other instruments. More often they are used as direct-reading working instruments. The Center is prepared to calibrate those used as reference instruments in the 0.5-percent accuracy class or better.

For the d-c calibration of electrical instruments (ammeters, voltmeters, and wattmeters), the basic standards are the standard cells and resistors, and the basic standard measuring apparatus is a potentiometer. The corrections for the standards are known and applied to obtain measurements of the highest accuracy.

Current and Voltage Transformers. The Center is equipped for calibration at 60 cps of current transformers having 5-amp secondary windings and primary current ranges of 0.1 to 4,000 amp, and voltage trans-



Final test of a 100-mc attenuator console, first instrument of this type in the new Center.

formers having 110- to 120-v secondary windings and primary-to-secondary voltage ratios of 1 to 120. At some future time, the Center expects to do most of these calibrations also at a frequency of 400 cps.

Other Standards. Other standards which can be calibrated include standard resistors for current measurements and voltboxes. Certain other ratio devices can be calibrated as the occasion arises.

No provisions have been made for calibrating watt-hour meters. At the present time, these are calibrated only at the Washington laboratories. Facilities for these and for other types of standards in the fields of electrical current, voltage, power, and energy may be added if the demand is great enough.

Typical of microwave equipment in the Electronic Calibration Center is this instrumentation for X-band attenuator calibration. Operator is using the I-F substitution method for calibrating an attenuator sent to the Center.

High-Frequency Region

In the high-frequency region (30 kc to 300 Mc), the Electronic Calibration Center is being equipped initially to calibrate standards of voltage (unbalanced), power, impedance, attenuation, and field strength. These standards are limited at present to those designed for continuous-wave measurements.

For each of the quantities to be measured, stable cw sources of high-frequency power and stable detectors or indicators are required. To achieve the desired frequency stability of the calibration system, crystal-controlled power sources and receivers are used wherever possible. In addition to good frequency stability and waveform, the sources must have very nearly constant power output. Power-stabilization circuitry has been developed that will hold constant the power output to better than 0.1 percent over long periods of time. Crystal-controlled superheterodyne receivers serve as monitors or detectors to give comparable frequency stability and to provide the necessary sensitivity. Most of the high-frequency instrumentation has been assembled in console form.

For most quantities, calibration services are planned primarily for the 9 fixed frequencies of 30, 100, and 300 kc, and 1, 3, 10, 30, 100, and 300 Mc. Other frequencies will be available for some quantities. In addition to the fixed-frequency apparatus, continuous-frequency coverage is being provided wherever feasible. However, this equipment will be less stable and less accurate.

High-Frequency Voltage. The instrumentation for high-frequency voltage calibration consists of stable transfer standards which operate over the desired range of voltages and frequencies. The range of voltage to be covered by presently planned equipment is from 1 μv to several hundred volts, and the frequency range is from 30 kc to 700 Mc (later to 1,000 Mc) at 13 fixed frequencies. The top limit of the voltage range will be lower at higher frequencies.

Voltage levels of 0.2 v and higher are covered by the voltmeter calibration consoles. The transfer standards used in these consoles are attenuator-thermoelement (AT) voltmeters. The attenuators are of the dissipative, capacitive, or waveguide-below-cutoff type. Dissipative attenuators are used at voltage levels up to 20 v. Above this level, the power requirements are so great that this type of attenuator is not practical. For higher voltage levels, capacitive attenuators are used at the lower frequencies and waveguide-below-cutoff attenuators at the higher frequencies. The AT voltmeters have been provided with a mount which permits a very short lead length between the standard and the meter under calibration. This mount is so constructed that any type of voltmeter can be connected by means of a simple adapter.

Employed in the voltmeter calibration consoles are fully shielded, stable, crystal-controlled sources. The consoles contain protective circuits that prevent overloading and consequent change in calibration of the standard voltmeters. These meters are calibrated in terms of the national standard of high-frequency voltage and provide a calibration accuracy of approximately 3 percent.

Voltages from 1 μv to 0.1 v will be covered by the microvolt calibration console. The transfer standard used in this console is the rf micropotentiometer, consisting of a coaxial rf resistor and a thermoelement. The thermoelement indicates the current through the resistor, and therefore the voltage across it. The resistors vary from 1 milliohm to 1 ohm to cover the voltage range. These resistors and thermoelements are so constructed that their response is essentially uniform over the required frequency range. Power from the rf sources in the voltmeter calibration console will be used also for the microvolt calibration console. A series of very sensitive fixed-frequency receivers, adjusted to have an input impedance of 50 ohms, transfers the reference voltage level from the micropotentiometer to an instrument undergoing calibration. The expected accuracy of calibration for the

lower frequencies is ±5 percent for the range 1 to 10 μv and ±3 percent for the range 10 μv to 0.2 v. The accuracy will decrease as the frequency increases.

High-Frequency Power. Three instruments provide high-frequency power calibration over a wide range of power levels: A thermistor bridge; a dry, static calorimeter; and a liquid-flow calorimeter. These three instruments offer a convenient means of establishing high-frequency power levels and for calibrating feed-through wattmeters.

The thermistor bridge is an equal-arm Wheatstone bridge with a thermistor in one arm. Power levels up to 100 mw can be measured over the frequency range 30 kc to 300 Mc with an accuracy of 0.5 percent. This accuracy limitation is due to substitution error and mount-efficiency considerations rather than to the bridge instrumentation itself. The accuracy is reduced to about 5 percent as the minimum power level of 0.1 mw is approached.

With calibrated attenuators and directional couplers, the range of the bridge can be extended to 100 w in the 100- to 300-Mc region. However, under these conditions the over-all accuracy of the apparatus is somewhat reduced.

The dry, static calorimeter consists of a special 50-ohm disk-type load resistor surrounded by a thick aluminum case. The load resistor has a very low temperature coefficient of resistance and provides a VSWR less than 1.20 for frequencies below 300 Mc. It is heated by applying rf power, and its temperature is indicated by the emf from a 50-junction thermopile.

Calibrating a decade capacitor at audiofrequencies, using a capacitor bridge.

The temperature of the aluminum case is kept constant to 0.002° C by a refrigeration unit and an electronically controlled heater cycling circuit. After equilibrium has been attained, the thermal emf is measured with a precision d-c potentiometer.

The thermal emf is calibrated in terms of applied d–c power. Over the frequency range 0 to 300 Mc the over-all accuracy is 1 percent for the power range of 20 mw to 12 w.

Nearing completion is a liquid flow calorimeter that is expected to be accurate to 1 percent over a range of 10 to 350 w at frequencies from 0 to 1,000 Mc. It measures the temperature rise of oil flowing past a load resistor. This temperature rise is monitored with a 10-junction integrating thermopile. A precision d-c potentiometer measures the thermal emf, and a calibrated flow meter measures the oil flow rate.

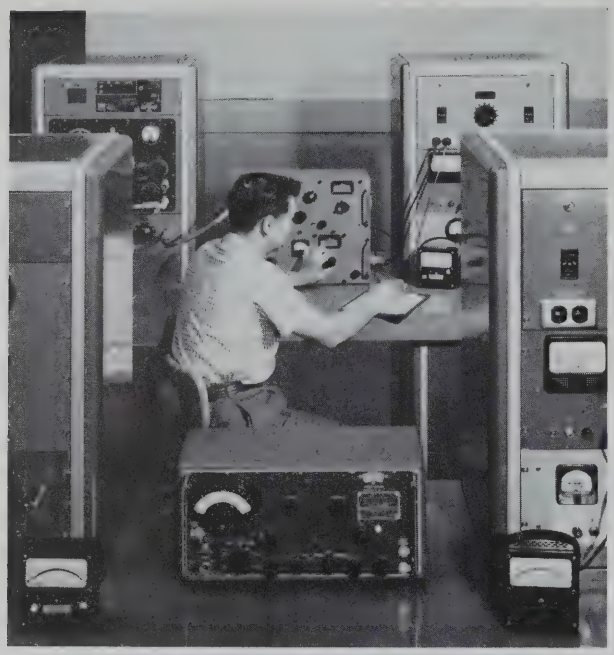
The thermal emf will be calibrated in terms of applied d–c power. An absolute calibration also can be made by determining the specific heat of the oil and making an independent calibration of the thermopile emf as a function of temperature difference.

High-Frequency Impedance. The standards of high-frequency resistance, inductance, and capacitance consist of stable components housed in shielded mounts. These standards are calibrated in terms of the national standard of high-frequency capacitance using susceptance variation techniques. The mounts have a special coaxial connector which mates with those on the impedance bridges used in the Center. This standardized connector was designed to provide a clearly defined reference plane and to minimize the effects of discontinuities in the connection, thus giving the standard a unique value. Such a connector reduces the loss of accuracy in transferring the value of the standard to any instrument with which it is to be used.

The values of the present set of standards range from 1 to 100,000 μμf for capacitance, 0.01 to 10,000 μh for inductance, and 1 to 100,000 ohms for resistance, with nominal values of 1, 2, or 5 times appropriate multiples of 10. These comprise a set of about 51 units, plus special mounts for combining units to obtain complex impedances.

The major portion of the impedance calibration services ultimately will be provided through the use of 18 bridges, each contained in a separate console and provided with its own individual exciter and detector. These bridges, currently under construction, will consist of an impedance and an admittance bridge for each of nine fixed frequencies. The design goal is to provide a direct-reading accuracy of 0.1 percent.

Four general-coverage bridges have been provided for interim use during the construction of the 18 fixed-frequency bridges and also for calibrations at frequencies other than those covered by the fixed-frequency instruments.



Attenuator and linearity calibrations are made on a high-frequency field-strength meter.

High Frequency Attenuation. To meet present-day accuracy requirements for high-frequency attenuator calibrations, complicated instrumentation designed and adjusted for a single, fixed-operating frequency is usually required. The fixed frequencies chosen by the Bureau meet the great majority of requirements, as determined by analysis of calibration requests over the past few years.

A recent development program has produced a superior waveguide-below-cutoff attenuator which extends the available calibration accuracy well beyond that of previous standards. Attenuators of this type will be used as attenuation standards in the Center. These are being incorporated into special calibration consoles, using a two-channel, null detection, direct-substitution measurement system. Pending completion of this instrumentation, a limited calibration service is being maintained using other equipment.

High-Frequency Field Strength. The Center offers a calibration service for field-strength meters in the frequency range from 30 cps to 300 Mc. The over-all linearity of the instrument, the internal attenuator ratios, and the antenna coefficients can be measured, and the instrument can also be calibrated as a two-terminal rf voltmeter. All calibrations are made in terms of sinusoidal voltages and currents. The instrumentation used for this work is continuously tunable over the radio part of the stated above frequency range.

The attenuator ratios and the over-all linearity of the field-strength meter are measured in terms of precision dissipative coaxial step-type attenuators, calibrated against a standard waveguide-below-cutoff attenuator. Field strength meters using either loop or dipole antennas can be calibrated.

Microwave Region

Microwave facilities are being provided at the Center to measure attenuation, power, frequency, and impedance. The frequency range to be covered extends from 300 to 40,000 Mc for attenuation, power, and impedance calibrations, and to 75,000 Mc for frequency calibrations. For components utilizing standard 3/8-in. rigid coaxial terminals with standard Type N connectors, calibrations will be made over the frequency range from 300 to 4,000 Mc. For components utilizing standard rigid rectangular waveguide terminals with standard waveguide connectors or flanges, calibrations will be made over the frequency range 2,600 to 40,000 Mc, and up to 75,000 Mc for frequency calibrations.

Microwave Attenuation. Attenuators are usually calibrated by the I-F substitution method. In this method, power is fed through the microwave attenuator and, after frequency conversion, through a standard 30-Mc attenuator. The standard is a cylindrical section of waveguide operated below cutoff and having attenuation properties that are accurately determined by calculation, precise construction, and evaluation. Microwave attenuators are calibrated in terms of this standard.

Due to limitations in the linearity of the frequency-conversion process, attenuation values above about 40 db are measured by the direct substitution method. In this method, microwave attenuators previously calibrated by the I-F substitution method are connected in series with the unknown and are used to determine its attenuation.

Microwave Power. Microwave power calibrations are made by comparing an unknown bolometer with a calibrated standard bolometer. In this method, stabilized continuous-wave power of a single frequency and constant level is fed into transmission-line terminals connected to the standard bolometer or to an unknown bolometer. Both the standard and unknown bolometers are considered as complete units consisting of a bolometer element in a suitable mount with a single pair of rf transmission-line terminals available for connection to the system.

A measurement at the same frequency of the reflection coefficient of the unknown bolometer is used to determine the reflected power. This in conjunction with the previous measurement, can be used to determine the actual power absorbed by the bolometer, and hence, its efficiency.

The standard bolometers have been carefully designed, fabricated, evaluated for all known errors, and calibrated in a microcalorimeter. All calibrations made by the Center are in terms of these bolometers. Different standard bolometers are used for each transmission line size.

Microwave Frequency. Frequency measurements for calibration purposes are made by direct comparison of the resonant frequency of a wavemeter cavity with the frequency of an accurately known signal (marker frequency). The basic reference standard for frequency measurements is a 100-kc signal obtained directly from the national standard of frequency. The 100-kc signal is multiplied through harmonic generation in conventional vacuum tubes and klystrons to provide several low- and high-frequency marker signals. These frequency marker signals become the references used in calibrating cavity wavemeters.

Microwave Impedance. At present, microwave impedance calibrations are not available at the Electronic Calibration Center. However, results of recent research in the Radio Standards Laboratory point the way to a calibration service, initially at X-band, within the next year, and work has begun on implementing this service.

NEW CAPACITANCE STANDARDS

AS PART of its continuing program to improve the precision and reliability of electrical standards and measurements, the Bureau has recently completed apparatus for the precise intercomparison of small capacitors.[1] The apparatus employs a special 3-winding transformer and a bank of very stable capacitors which are combined to balance the unknown capacitance. This apparatus improves both the sensitivity and precision of capacitance measurements [2] made by Bureau laboratories.

To fully realize this advantage, an improved absolute standard of capacitance has also been constructed. Its design, based on a recently discovered theorem in electrostatics,[3] allows its value to be calculated in terms of a single measured length. It is believed that the uncertainty in the value assigned to this standard does not greatly exceed 1 part in a million.

The bridge techniques and the calculable standard offer immediate gains in the accuracy of capacitance measurements. In addition, they provide an opportunity for an absolute-ohm determination in terms of capacitance and frequency. By this method, the Bureau hopes to improve the value assigned to the primary standard of resistance, which is presently based on a calculable inductance and frequency. Work aimed at this goal is in preliminary stages.

The basic principles of transformer bridges have been known for many years and a number of such bridges have been constructed during the past two decades.[4] However, their possibilities were never fully exploited before the recent work of A. M. Thompson [5] and his colleagues at the Australian National Standards Laboratory. The Bureau, in order to advance its techniques in this field of measurement as rapidly as possible, arranged for M. C. McGregor of the Australian laboratory to come to Washington and work with the staff of the Electricity and Electronics Division. J. F. Hersh of the General Radio Company, Concord, Massachusetts, also made substantial contributions to the program while a guest worker at the Bureau.

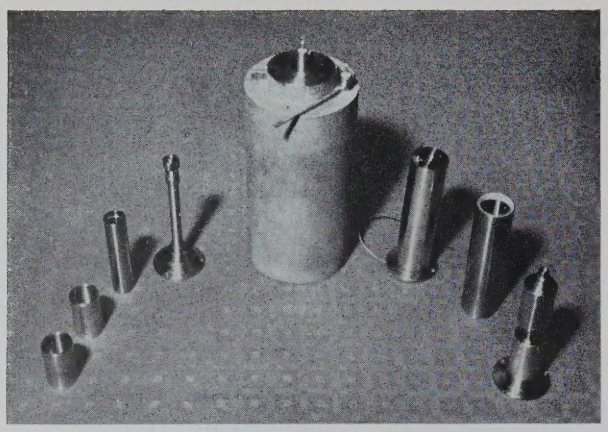
The ratio arms of the capacitance bridge are the two secondary windings of a special 3-winding transformer, the third winding being a common primary. The induced secondary voltages, essentially equal to the voltages at the terminals of the capacitors being compared, depend on the number of turns in each secondary winding. By appropriate construction, the terminal voltage ratio has been made equal to the turns ratio within a part in 10 million. Knowing the ratio of the voltages supplying an unknown and a known capacitance permits the direct determination of the unknown. This is accomplished by balancing the bridge through the adjustment of a bank of known, stable 3-terminal capacitors. The balance value multiplied by the voltage ratio is the capacitance of the unknown, and this value can be determined with a precision not previously possible. For example, when 1 pf (1 $\mu\mu$f) capacitors are compared, differences as small as 10^{-6} pf can be easily measured. Although balancing values up to 1 μf are provided, the apparatus is most effective in comparing capacitors of less than 10,000 pf.

The new capacitance standard was designed to improve the accuracy of capacitance determinations to the level made possible by the transformer bridge. This standard is dependent only on the lengths of two cylinders when certain symmetry conditions are fulfilled and end effects eliminated. The capacitance is defined in terms of two 10-in. gage bars whose lengths can be measured mechanically to an accuracy considerably better than 1 part in a million. Evaluation of the various sources of error in the transformer bridge and in the calculable standard leads to the conclusion that values of capacitance assigned from it are accurate within 3 parts in a million at the 1 pf level.

Lampard's Theorem

The new theorem in electrostatics on which the calculable capacitor design is based is known as Lampard's theorem. It states that four parallel cylindrical electrodes arranged to fulfill certain symmetry conditions have a direct capacitance of $\ln 2/4\pi$ [2] electrostatic units for each centimeter of cylinder length.

A simple way of meeting the requirements of Lampard's theorem is to arrange four cylindrical bars so that their axes are all parallel and the centers of the circles which form their cross sections lie at the corners of a square. The two bars on one diagonal of the square can then be used as the active electrodes,



Temperature-compensated capacitors, designed at the Bureau as secondary standards to maintain the unit of capacitance. Components left to right: Two duralumin guard electrodes, brass inner electrode, central supporting post, assembly in case ready for hermetic sealing, assembled capacitor, brass outer electrode, and partially assembled capacitor showing inner and guard electrodes in place.

and the other two bars, connected to a surrounding enclosure, can be used for the third (or screening) electrode.

Lampard's theorem specifies the capacitance per unit length exactly only if the cylinders are infinite in length. However, in the practical case, a bar with a removable section allows the difference between two measurements to be determined—this difference representing the capacitance of the removable section. The end effects are the same in the two measurements and can be eliminated by using the difference technique. By measuring the length of the removable section, the capacitance associated with this length can be computed.

Bridge Construction

The very great accuracy with which bridge measurements can be made is due mainly to the construction of the acting source of voltage—the transformer. The capacitance evaluation depends on knowing precisely the ratio of terminal voltages, and this, in turn, depends upon the stability and exactness of the ratio of the induced voltages in the transformer windings. To induce voltages having a stable, known ratio to one another—that is, depending only on the turns ratio of the secondary windings—careful consideration must be given to all the elements of the transformer, its core, primary, secondaries, and shield. The transformer primary, wound on a toroidal core of high permeability and large cross section, is designed to provide a uniform distribution of magnetomotive force. Furthermore, to insure that the core flux generated by the primary winding is the only source of voltage in the two secondary windings, copper shields are used to enclose the primary completely; secondaries are also shielded. As both secondary windings are uniformly distributed around the toroid and are closely interleaved, they link practically identical fluxes. Consequently, the ratio of their induced voltages, as desired, is stable and capable of precise evaluation.

The secondary windings are so constructed that their resistances and leakage reactances are very small. They may, therefore, be loaded in the bridge with impedances as low as 1,000 ohms before their ratio is affected by as much as 1 part in a million.

The bridge technique is particularly adapted to the comparison of 3-terminal capacitors in which the active electrode pair is completely enclosed and shielded from external fields by a third electrode. The 3-terminal arrangement allows the direct capacitance between the first two electrodes to be defined, and prevents the capacitance to the screening electrode from affecting the bridge balance. The capacitance can therefore be adjusted by causing the screening electrode to extend between the active electrodes. As the screen intercepts part of the electric field between the electrodes, the capacitance is altered: The smaller the hole through which the active electrodes "see each other", the less is the direct capacitance. By controlling the size of the hole in the screen, 3-terminal capacitors can be constructed with values as small as 10^{-5} pf.

[1] *For further technical details, see* New apparatus at NBS for absolute capacitance measurement, *by M. C. McGregor, J. F. Hersh, R. D. Cutkosky, F. K. Harris, and F. R. Kotter, Proc. IRE (in press).*

[2] Standards for low values of direct capacitance, *by C. Moon and C. M. Sparks, J. Research NBS* **41,** *497 (November 1948).* Standards of very small capacitance, *NBS Tech. News Bul.* **32,** *49 (May 1948).*

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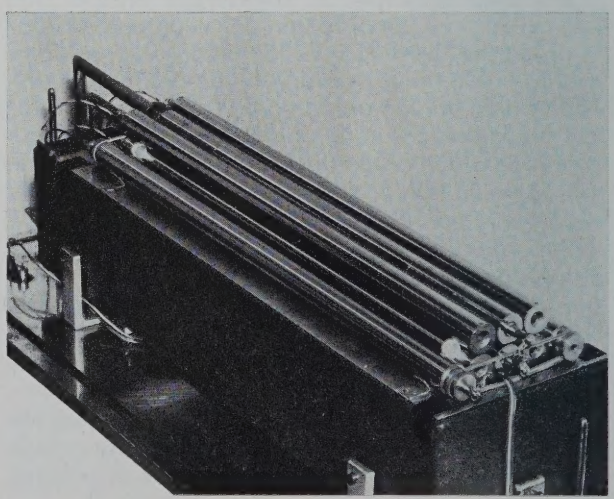
Improved standard of capacitance. The design, based on a recently discovered theorem in electrostatics, allows capacitance value to be calculated in terms of length. Removable sections of center cylinder eliminate end effects.



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SINCLAIR WEEKS, *Secretary*
NATIONAL BUREAU OF STANDARDS
A. V. ASTIN, *Director*

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